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J. C. Ferreira

Microstereolithography using digital micromirror devices

ABSTRACT

The development of a high-resolution projection microstereolithography (PμSL) apparatus by using the Digital Micromirror Device (DMD™ , Texas Instruments) as a dynamic mask is presented in this paper. The DMD™ is a new display device fabricated by the micromachining technique and serves as an ultraviolet exposure system that is utilised in applications for projection exposure systems and rapid prototyping. The PμSL apparatus based in DMD™ present some difficulties in the adjustment mechanisms that are analysed. This unique technology provides the hability to fabricate complex three-dimensional microstructures used for micro electro-mechanical systems (MEMS).

The fabrication of smallest features with an accuracy of 0.5 μm has been calculated. At the end some conclusions are reached.

INTRODUCTION

The microstereolithography is a Rapid Prototyping (RP) process used to fabricate microparts. The principle of microstereolithography is the same as stereolithography RP technique [1], i.e., allow drawing cross sections on a photopolymer surface by means of UV light. However, the resolution required for a microstereolithography system is much finer.

Microstereolithography systems developed can be divided into two main categories:

- Scanning Micro Stereolithography systems (SμSL) [2-4] and
- Mask Projection Micro Stereolithography systems (PμSL), or Integral micro stereolithography systems [5-10].

The mask projection microstereolithography systems based in digital micromirror devices have the following advantages over scanning microstereolithography systems:

- Mask projection microstereolithography is faster than the scanning microstereolithography because vector-by-vector scanning is a slower process.

• The accuracy of PµSLA is better because the errors introduced by the X-Y translation stages are avoided. The only mobile element in the PµSLA systems during the fabrication process is the Z-Stage.

Due to these advantages, current research on projection microstereolithography systems is focused on mask projection (DMD™) for microstereolithography.

WORKING PRINCIPLE OF THE PµSL SYSTEM

Similar to the conventional stereolithography process, the PµSL systems allows fabricating complex 3D microstructures in a layer-by-layer fashion [1]. The shapes of these constructed layers are determined by slicing the CAD model with a series of closely spaced horizontal planes. By taking the sliced layer patterns in the electronic format, the mask patterns are dynamically generated as bitmap images on a computer-programmable array of digital micromirrors on the DMD™ chip. The UV light illuminated on the DMD™ chip is shaped according to the defined mask pattern, and then, the modulated light is transferred through a reduction lens system over the photo-curable resin surface. Hence, an image is formed on curable resin surface with a reduced feature size. In each layer, the illuminated liquid photo-polymer area is solidified simultaneously under one exposure, while the dark regions remain liquid. After the fabrication of one layer, the substrate is immersed into the UV curable resin and the new layer is fabricated on top of the existing solid structure. A complex, geometrically shaped microstructure can be fabricated by building all the layers sequentially and stacking them from bottom to top. The developed PµSL system is schematically shown in Fig. 1.

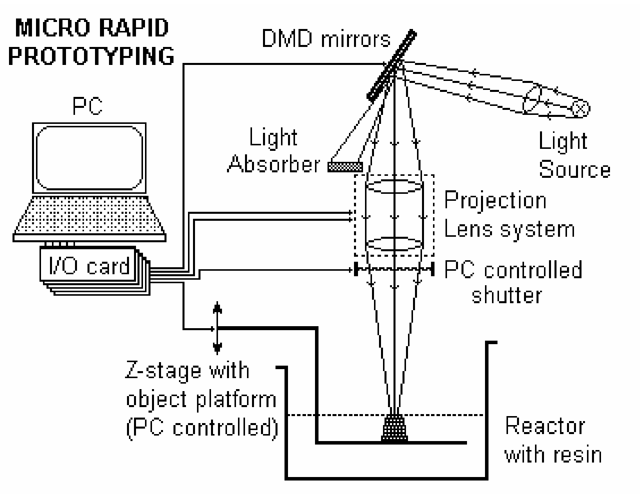

Figure 1: Diagram of the PµSL system using DMD™.

The PμSLA system could provide a parallel fabrication of complex three-dimensional microstructures used for microprototypes including the micro electro-mechanical systems (MEMS) [11].

PμSL COMPUTER ANALYSIS AND ADJUSTMENT CONTROL

The PμSL apparatus is PC operated by four mechatronic system modules and one analysis module, Figure 2.

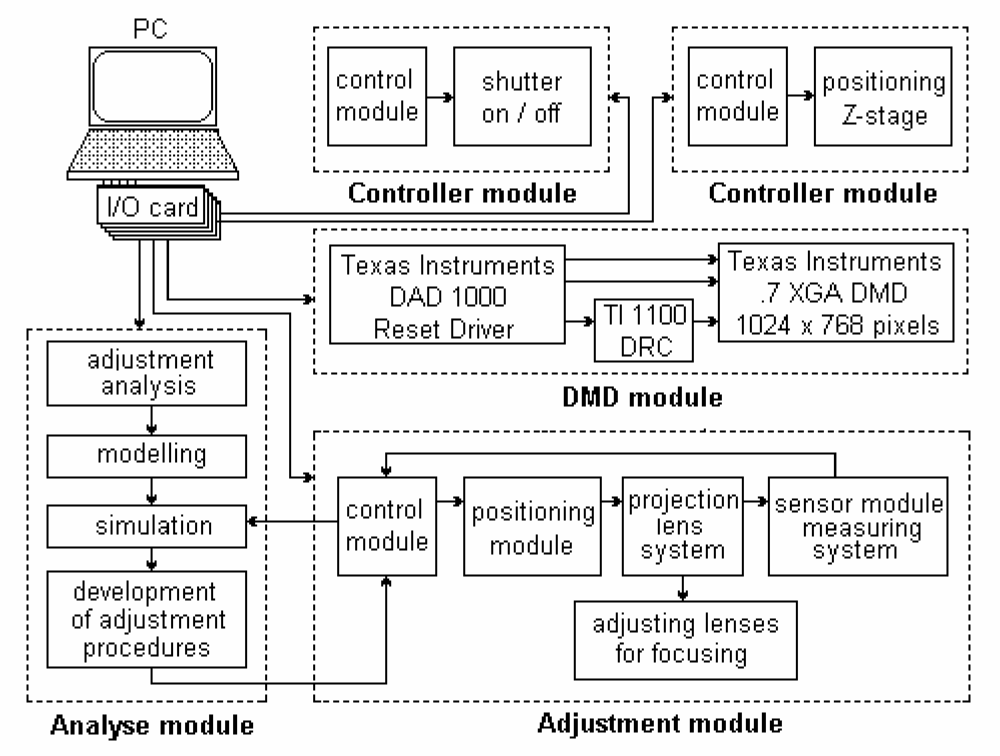

Figure 2: Computer procedures to analyse / control / adjust the PμSL apparatus.

The analyse module integrates the adjustment analyisis based on the development of adjustment procedures. This module could also integrate the process modelling and the process simulation.

One of the control modules simply commands the shutter system on/off that is programmed in time via software function of the photocurable resin reaction delay.

Other of the control modules commands the Z-stage to focuse the UV light over the the photocurable resin level.

The DMD Discover™ 1100 module has at the heart the TI 0.7 XGA DDR DMD™

semiconductor that allows to manipulate light digitally. When integrated with light source and optics the DMD™ spatial light modulator creates binary light patterns with efficiency and precision.

The adjustment module is linked to sensor measuring systems that allows controlling automaticaly the position of the projections lens system to adjust the lenses for focusing.

PμSL ADJUSTMENT VIA NC CONTROL

The PμSL apparatus based in DMD™ present some difficulties in the adjustment mechanisms that are analysed. The theoretical development of adjustment matrix equations [12-13] that guide the optical mechatronic system, based in automatic computer procedures to analyse and automatically adjust the microprojection lens system in the course of microstereolithography, yielding that focusing and optical axes stay aligned with the greatest precision to increase the prototypes geometry accuracy. The adjusting mechatronic system, for the microprojection lens focus, is set in motion by a numerical control (NC) or by an auto-numeric control system, schematised in Figure 3.

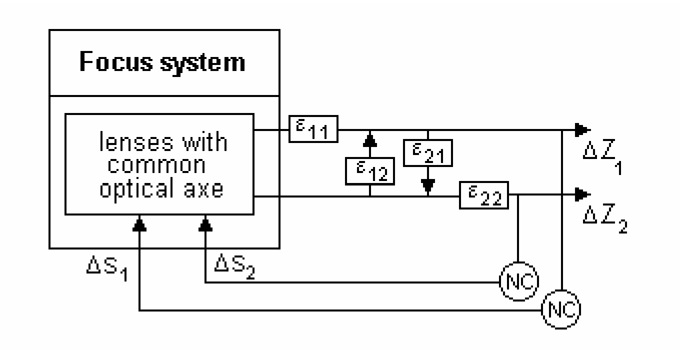

Figure 3: Auto-numeric control to adjust the microprojection focus system.

The Z-axis lens focusing is necessary until the projected image is well defined on the surface resin level. An influence with the *Z* automatic position module around ΔS_1 and ΔS_2 leads only to variations of the focus situation $F_1 \cong F_2$ around ΔZ_1 and ΔZ_2. Under use of linear approximations, the matrix equation (1) arises:

$$\begin{bmatrix} \Delta Z_1 \\ \Delta Z_2 \end{bmatrix} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} \\ \varepsilon_{21} & \varepsilon_{22} \end{bmatrix} \cdot \begin{bmatrix} \Delta S_1 \\ \Delta S_2 \end{bmatrix} \qquad (1)$$

When the lens focus converges on the resin surface level the matrix extreme values (ε_{12}

and ε_{21}) become very small or null. It now follows mathematical connection calculation. In result of that, the matrix solution is simplified and become equation (2):

$$\begin{bmatrix} \Delta Z_1 \\ \Delta Z_2 \end{bmatrix} = \begin{bmatrix} \varepsilon_{11} & 0 \\ 0 & \varepsilon_{22} \end{bmatrix} \cdot \begin{bmatrix} \Delta S_1 \\ \Delta S_2 \end{bmatrix} \tag{2}$$

EXPERIMENTAL PμSL APPARATUS

The experimental PμSL apparatus developed in this research work, using a DMD™, is composed by: UV light source with a light guide (emitting radiation from 300 to 470nm with a peak at 365nm); condenser lens system for UV homogeneous light incidence on the DMD™; Digital Micromirror Device from Texas Instruments; set of focusing lens system to project the bitmap image displayed on the DMD™ onto the resin surface; photopolymer bath; x-y-z movable stage; and two interlinked computer controller systems, as shown in Figure 4.

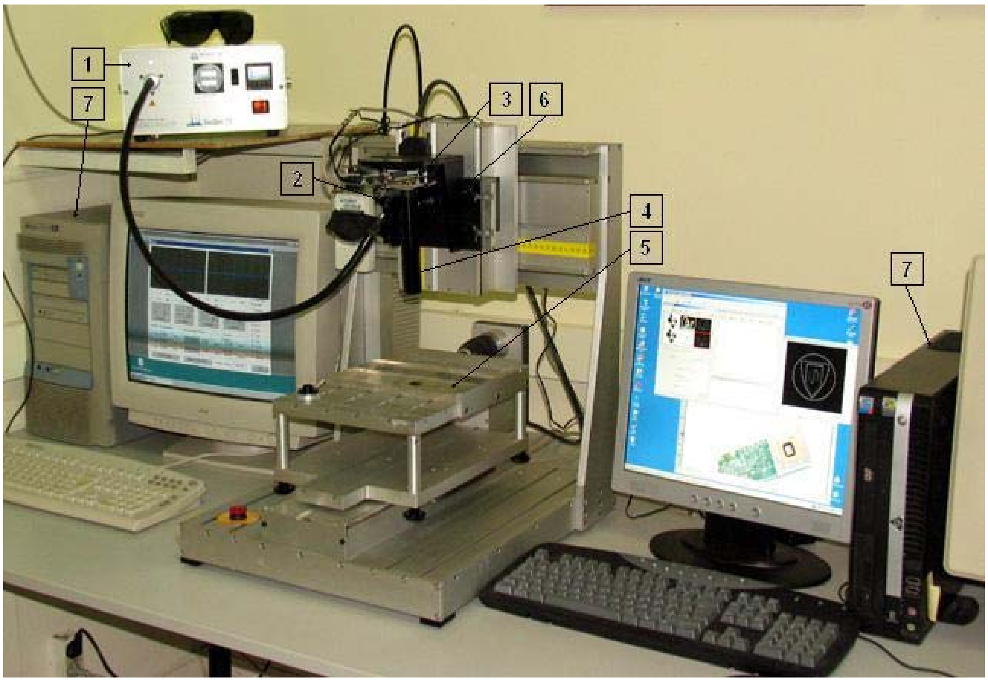

Figure 4: Experimental PμSL apparatus using a DMD™: (1) UV light source with a light guide, (2) condenser lens system; (3) DMD™; (4) focusing lens system; (5) photopolymer bath; (6) x-y-z movable stage; and (7) interlinked computer controller system.

PμSL SYSTEM ACCURACY

The process of curing a single layer using the PμSL system is analytically modeled as the "Resine layer cure model".The layer cure model is formulated in two steps. First, the irradiance received by the resin surface is modeled as a function of the system parameters (irradiance model). Then, the resin used in the system is characterized to experimentally determine its working curve. The irradiance model and the resin characterization enable one to compute the dimensions of any layer cured using the PμSL system in terms of the process parameters. The resine layer cure model has been validated by curing test layers on the developed PμSL system. The resine layer cure model, which is composed of the irradiance model and the cure model can thus be presented in the form of the following set of equations:

$$H(pr_i) = \left(H_{av} x \Big/ \sum_{j=1}^{n} w_j m \right) \sum_{j=1}^{n} \sum_{k=1}^{m} \delta \left(pr_i, p_j, v_k, o, i, \alpha, d, d', \phi \right) \quad (3)$$

where

$H(pr_i)$ is irradiation received at point pr_i on the resin surface,

H_{av} is the average irradiance received by the resin surface,

w_j is the weight given to the ray, calculated as $w_j = 1\text{-}0.00086p\text{-} 0.00883p^2$ where p is the distance of the point on the pattern from which the ray is emanating from the center of the beam incident on the DMD™,

$\delta(pr_i, p_j, v_k, o, i, \alpha, d, d', \Phi)$ is a ray tracing function that operates on the imaging system parameters to determine whether the ray starting from pattern point p_j in the direction of vector v_k will intersect the point pr_i on the resin surface or not,

$n \to \infty$, $m \to \infty$

Cured layer is a collection of points satisfying condition:

$L(pr_i) = 1$

$L(pr_i) = 1$ if and only if $C_d(pr_i) \geq LT$

$C_d(pr_i) = D_p \ln (H(pr_i)\ TOE/E_c)$

$C_d(pr_i)$ is the cure depth at the point pr_i on the resin surface,

$H(pr_i)$ is the irradiance received by the point pr_i on the resin surface

LT is the layer thickness used to build the micropart

TOE is the time for which the pattern is imaged onto the resin surface

D_p is the depth of penetration of the resin

E_c is the critical exposure of the resin

Using the resine layer cure model, the limit on the lateral positive resolution of the PμSL system can be quantified. A line of micromirrors one micromirror thick shall cure the thinnest feature. By running a bitmap of size 5 pixel x 1 pixel through the resine layer cure model, the thickness the aerial image over the photo-curable resin is found to be 1.9 µm. In order to validate this limit, the curing of a line one pixel thick was attempted. However, the line couldn't withstand the rinsing under alcohol to clean the liquid photopolymer resin excess. Nevertheless, since the resine layer cure model has been validated, it can be concluded that the limiting resolution computed using it would be correct. In order to check the validity of the resine layer cure model for very small features, a line 3-pixel wide was cured. This line could withstand the cleaning procedures. The resine layer cure model computed the width of the cured line to be 6.2 µm. The width of the actual line cured was found to be 6.0 µm. The picture of the line solidified in SOMOS 10120 photo-curable resin is shown in Figure 5. This shows that the resine layer cure model is valid even for small feature sizes.

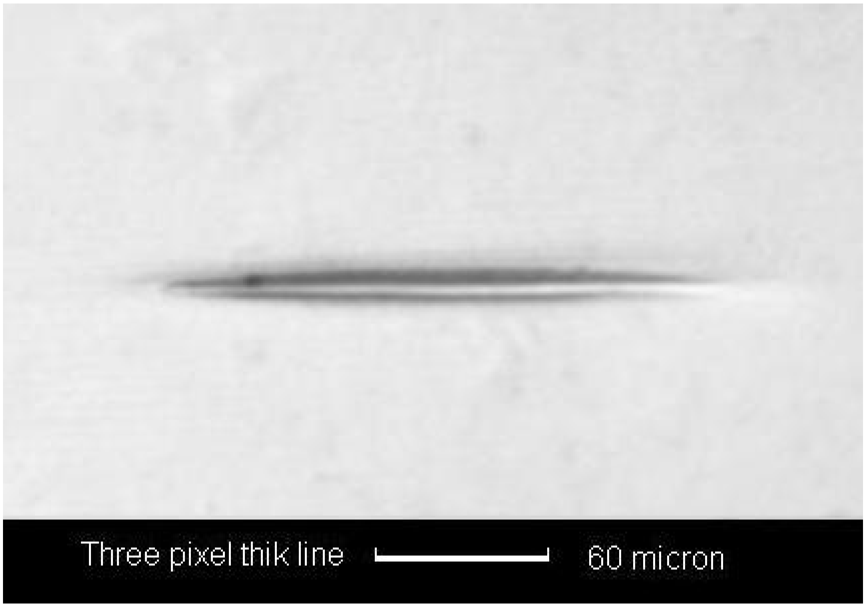

Figure 5: Three-pixel wide line cured on the PµSLA apparatus (SOMOS 10120 resin).

To specifie the theoretical limiting resolution of the system it needs to be known the diffraction limit on the minimum feature size that can be irradiated by the imaging lens that shoud be smaller than 1.9 µm. Resolution of the imaging system is determined by the wavelength and the numerical aperture using the Rayleigh's formula [14],

$$D = \frac{k_1 \lambda}{NA} \tag{4}$$

where D is the minimum dimension that can be printed, λ is the exposure wavelength and NA is the numerical aperture of the imaging lens, and the proportionality constant k_1 is a dimensionless number in an approximate range from 0.6 to 0.8.

As the numerical aperture of the imaging lens is 0.592, the diffraction-imposed limit on the resolution of the imaging system is D=0.493 μm. Consequently the fabrication of microstructures with small features with an accuracy of 0.5 μm could be achieved.

CONCLUSIONS

- In this work, a PμSL system has been successfully developed to fabricate accurately 3D microstructures.
- The developed PμSL system allows manufacturing microprototypes in photo-curable resin with small features with an accuracy of 0.5 μm.
- The DMD™ module integrated with an UV light source and optics allows manipulating light digitally generating binary light patterns with efficiency and precision for microstereolithography.

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